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Spent Fuel Characteristic Analysis with Realistic Irradiation History

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1. Introduction

The safe management of the spent fuels of PWR and CANDU reactors is one of the most urgent problems that should be resolved in nuclear industry in spite of the new energy policy to reduce the electricity generation by nuclear power plants. In particular, the necessities of dry storage of PWR spent fuels have been increased because the capacities of spent fuel storage pools in reactor buildings are expected to be saturated in the near future. Therefore, the efficient evaluation of source terms is increasingly required for safety analysis of the spent fuel storage facilities. Recently, we have developed AMORES (Automatic Multiple ORIGEN Runner for Evaluation of Source Terms) which can estimate the characteristics for a huge number of spent fuels with ORIGEN-S [1, 2]. However, the depletion and decay calculations of AMORES did not consider the detailed irradiation and cooling histories of the individual spent fuel in the reactor cores but it used a simple assumption that all the fuel assemblies for PWRs have undergone a single specific power over a depletion period estimated with the discharge burnup. However, it was not proven that this approach gives the conservative estimations of the spent fuel characteristics such as the radioactivity, inventories of major nuclides, heat generation, and so on.

The purpose of this work is to analyze the effects of the realistic irradiation and cooling histories of the spent fuels on the characteristics of the spent fuels. In particular, this analysis is based on the characterization of irradiation and cooling patterns of the spent fuels included in the spent fuel data base provided by KHNP. The ORIGEN-S code was used to evaluate the spent fuel characteristics with realistic irradiation and cooling histories and the STARBUCS sequence of SCALE6.1 for the effects of them on the criticality.

2. Methods and Results

To start the analysis with the realistic irradiation and cooling histories of spent fuels, we first analyzed the patterns of irradiation and cooling for the spent fuels included in the spent fuel data base provided by KHNP. Actually, the spent fuel data base includes the detailed information such as the initial uranium enrichment, discharge burnup, the final discharged date, the cycle numbers during which each fuel assembly is irradiated, and so on. The AMORES program originally did not considered the irradiation and cooling histories for simplicity but it assumed a single specific power of 40MW/MTU and used the irradiation (or depletion) time which is estimated by dividing the discharged burnup with the specific power for all the PWR spent fuel assemblies. From the analysis of the patterns, we selected the representative eight patterns (Cases A ~ H) that are used in the detailed analysis. The selected patterns of the irradiation and cooling histories are shown in Fig. 1. As shown in Fig. 1, for example, the Case A represents that the fuel assembly is irradiated the first and second cycles, cooled down over the next five cycles followed by the one cycle irradiation and then discharged while the second case (i.e., Case B) represents a simple pattern in which the fuel assembly is irradiated over the first three cycles and then discharged from the reactor.

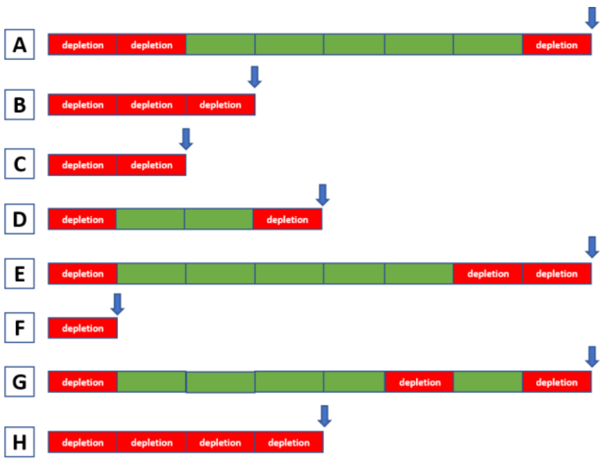

Fig. 1. Representative Patterns of Irradiation and Cooling of Spent Nuclear Fuel Assemblies

In this work, the irradiation time interval for each cycle was first estimated using the discharge dates for the cycles specified in the spent fuel data base. For example, the irradiation time interval for the first cycle is just the difference between the start date of reactor operation and the one of the discharge data after the first cycle while the ones for the subsequent cycles are the differences between the discharge dates after the previous and present cycles. Then, the specific power is estimated by multiplying the discharge burnup and the total irradiation time (i.e., summation of all the irradiation time intervals over all the cycles). The cooling times between cycles are explicitly modeled in the ORIGEN-S calculations. Table I summarizes the specifications of the considered spent fuel assemblies corresponding to the representative irradiation and cooling history patterns given in Fig. 1. In the ORIGIN-S calculations, the 'ce16x16' and 'w17x17_ofa' one group cross section libraries given in SCALE 6.1 were used for the 16x16 and 17x17 fuel assembly types, respectively [3].

Table I: Specification of the considered spent fuel assemblies corresponding to the representative patterns of irradiation and cooling

ID	Pattern type	Initial Enrichment [wt% ^{235}U]	Initial Uranium Mass [g]	Discharge Burnup [MWD/MTU]	Number of Cycle	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	Discharge Date
KY3B009	A	2.359	432,251	32,171	3	1	2	8		2004-10-13
KY3B001	B	2.368	432,384	25,684	3	1	2	3		1998-04-14
KY3Q041	C	4.499	429,707	41,780	2	13	14			2012-10-26
KY3B103	D	2.348	430,441	25,617	2	1	4			1996-06-17
KK4C42	E	3.10	458,969	39,965	3	1	7	8		2004-10-13
KY3A034	F	1.30	431,528	12,259	1	1				1996-02-26
KK3C11	G	3.10	461,068	28,748	3	1	6	8		2004-10-13
KY4E008	H	4.12	430,460	46,207	4	2	3	4	5	2000-10-12

Table II summarizes not only the specific powers and the irradiation time interval (i.e., depletion time) estimated with the method describe above but also the various spent fuel characteristics estimated at 2035.01.01 using ORIGEN-S with the irradiation and cooling histories. The numbers in the parenthesizes represents the discrepancies (in %) between the estimated values with the original simple method used in AMORES and the new method with consideration of irradiation and cooling histories. As shown in Table II, the consideration of irradiation and cooling histories gives much smaller specific powers for all the cases except for the Case C than 40MW/MTU used in AMORES while it gives significantly longer irradiation time intervals. The cooling time given in Table II includes the cooling times between the irradiation cycles and the cooling time after the final discharge from the reactor. As expected, the consideration of the irradiation and cooling histories does not give the differences in the inventories but it gives the underestimation of the radioactivities and gamma powers for the most cases than the original method used in AMORES. The underestimation in radioactivity is due to the longer cooling times except for the Cases C and F. On the other hand, the discrepancies in thermal powers are not so large but the consideration of irradiation and cooling histories gives lower gamma power except for the Cases C and F similarly to the trend in radioactivity. In addition, it should be noted that the consideration of irradiation and cooling histories gives higher radiotoxicities (i.e., conservative estimation) for the most cases. Specifically, the discrepancies are large for the Case A.

Table II: Comparison of Spent Nuclear Fuel Characteristics

Characteristic parameters	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Specific power [MW/MTU]	27.07 (-47.7%)	23.12 (-73.0%)	42.84 (6.6%)	33.68 (-18.8%)	28.91 (-38.4%)	36.92 (-8.3%)	25.64 (-56.0%)	28.41 (-40.8%)
Depletion day [Day]	1188.30 (32.3%)	1110.71 (42.2%)	975.18 (-7.1%)	760.64 (15.8%)	1382.31 (27.7%)	332.00 (7.7%)	1121.10 (35.9%)	1626.55 (29.0%)
Cooling time [Day]	13325.1 (17.2%)	13400.6 (0%)	8095.7 (0%)	13750.3 (5.7%)	10426.6 (20.7%)	14179.5 (0%)	16857.6 (11.7%)	12274.1 (0%)
Inventory [g]	432390 (0%)	432430 (0%)	429680 (0%)	430450 (0%)	459010 (0%)	431554 (0%)	461100 (0%)	430430 (0%)
Radioactivity [W]	83760 (-7.3%)	61250 (-1.7%)	148480 (0.4%)	62620 (-1.8%)	138710 (-4.2%)	29206 (1.9%)	63520 (-5.1%)	115640 (-1.8%)
Thermal power [W]	322.1 (1.3%)	223 (-0.5%)	477.1 (0.1%)	227.9 (0.6%)	471.8 (-2.1%)	104.5 (2.3%)	243.3 (-1.4%)	439.8 (-0.9%)
Gamma power [W]	70.38 (-8.7%)	52.01 (-1.6%)	121.29 (0.2%)	52.6 (-2.5%)	117.6 (-4.3%)	24.1 (0.6%)	54.4 (-5.4%)	99.1 (-1.5%)
Inhalation hazard [m^3 of air at RCG]	2.65E+17 (20.9%)	1.62E+17 (1.6%)	2.78E+17 (-0.1%)	1.69E+17 (6.1%)	3.02E+17 (4.1%)	7.99E+16 (5.5%)	1.81E+17 (6.0%)	3.18E+17 (0.6%)
Ingestion hazard [m^3 of water at RCG]	8.47E+10 (6.2%)	5.74E+10 (0.1%)	1.17E+11 (0.1%)	5.90E+10 (2.0%)	1.16E+11 (-0.6%)	2.75E+10 (3.0%)	6.30E+10 (0.5%)	1.12E+11 (-0.4%)

To better understand these trends, we analyzed the nuclide-wise contributions to radioactivity, thermal power, and radiotoxicity (i.e., inhalation hazard) for the Case A. The results of the analysis are given in Fig. 2. In Fig. 2, we consider only ten nuclides giving significant contributions. For radioactivity, the largest contribution is from ^{137}Cs and the next significant contributions are from ^{137m}Ba, ^{241}Pu, ^{90}Sr, and ^{90}Y in the order of magnitude. The contribution from these five nuclides to radioactivity is ~94% of the total radioactivity.

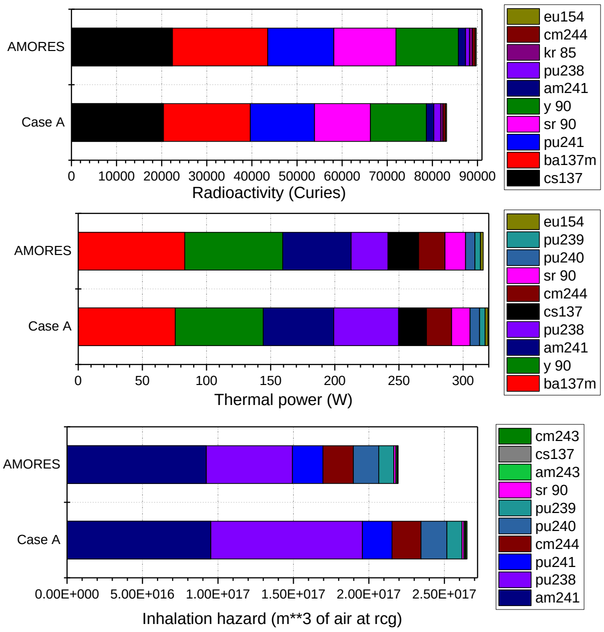

Fig. 2. Nuclide-wise contribution analysis results of Case A

On the other hand, the significant contribution to thermal power are from ^{137m}Ba, ^{90}Y, ^{241}Am, ^{238}Pu, and ^{137}Cs in the order of magnitude and their contributions are ~84% of the total thermal power. This figure also shows that the discrepancies between AMORES and the new method using irradiation histories are large for the nuclides having large contributions. In particular, for the radiotoxicity, ^{238}Pu gives the largest contribution and the discrepancy in the radiotoxicity between AMORES and the new method with irradiation history consideration is also largest (~75.9%) and it is due to the fact that ^{238}Pu has relatively a short half-life of 87.7 days.

Next, we analyzed the effects of the consideration of irradiation and cooling histories on the criticality safety. The criticality safety analysis was performed using the STARBUCS sequence of SCALE6.1 and 238 group ENDF/B-VII cross section library for the GBC-32 computational dry storage cask [4]. The geometric modeling using STARBUCS is shown for the spent fuel assembly of 17x17 lattice structure in Fig. 3. We considered separately the burnup credit with the major actinides (i.e., ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, O) and the one with the major actinides and fission products (i.e., ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{237}Np, ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{143}Nd, ^{145}Nd, ^{151}Eu, ^{153}Eu, ^{155}Gd, O). These nuclides are described in NUREG/CR-6747 [5].

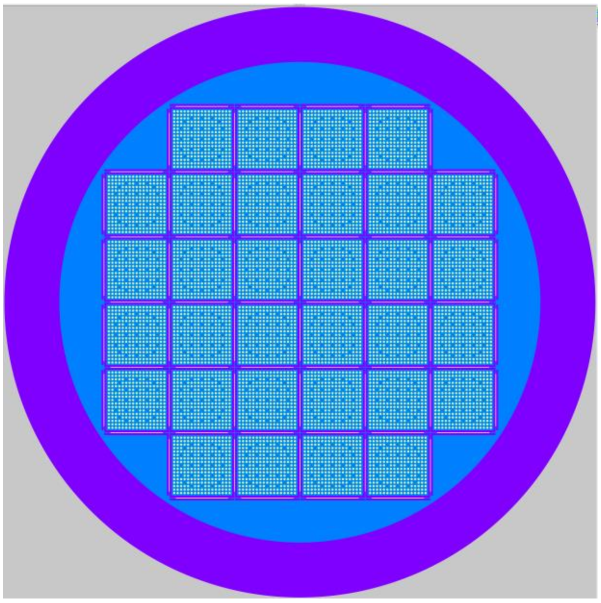

Fig. 3. STARBUCS model of the GBC-32 cask

The effective multiplication factors (k_{eff}) are compared in Table III. Table III shows that the consideration of irradiation and cooling histories gives significantly higher k_{eff} values (i.e., conservative) than the AMORES simple method.

Table III: k_{eff} values and discrepancies in k_{eff} between AMORES and the new method for the GBC-32 cask

Major actinides								
	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
AMORES	0.66435	0.69442	0.79517	0.69431	0.69154	0.68137	0.74290	0.69341
New	0.73242	0.77220	0.87066	0.77181	0.78437	0.72013	0.84936	0.81021
Difference [pcm]	13989	14505	10904	14461	17113	7900	16872	20791
Actinides and major fission products								
	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
AMORES	0.56613	0.60531	0.67558	0.60576	0.57802	0.62468	0.64373	0.57140
New	0.65302	0.70247	0.76865	0.70020	0.68960	0.67520	0.77061	0.70697
Difference [pcm]	23503	22851	17923	22266	27991	11976	25577	33558

For the burnup credit with major actinides and major actinides plus fission products, the largest discrepancies were estimated to be 20791 pcm and 33558 pcm, respectively, for Case H. These results show that the consideration of irradiation and cooling is very important to accurate and conservative estimation of the criticality.

3. Conclusions

In this work, the effects of the consideration of irradiation and cooling histories of spent fuel assemblies on the source terms and criticality were analyzed using SCALE6.1 for the eight representative patterns of irradiation and cooling history given in the spent fuel data base provided by KHNP. As the results, it was shown that for the most cases the consideration of irradiation and cooling histories gives more conservative estimation of the radiotoxicities while the characteristic parameters of the spent fuel were underestimated with the consideration of irradiation and cooling histories. The criticality analysis with burnup credit for the GBC-32 benchmark cask showed that the consideration of irradiation and cooling histories gives significantly higher k_{eff} values than the simple AMORES method. From these analyses and results, it is concluded that the consideration of irradiation and cooling histories is very important for realistic and conservative (for radiotoxicity and criticality) estimations of the spent fuel characteristics for safety analysis of dry storage facilities.

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